Modifying 1960 MHz High Power Solid-state Amplifiers for 13 cm

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A much longer version of this paper is on the Conference DVD, with many more pictures, examples and supporting files.☆

After doing some work on my own PA design for 1296 MHz, converting some 900 MHz amplifiers for 1296 MHz [1] and looking at the work done by Chris Bartram GW4DGU on similar amplifiers, I decided to tackle some 2.3 GHz conversions.

This was quite timely, because as cellular phone systems have expanded, there has been large scale replacement of inefficient PAs.

Available Amplifiers and their Configuration

These older amplifiers operating in the 1960 MHz or 2100 MHz band had an original specification in the order of 30 W per carrier, so a multi carrier CDMA amplifier typically had the potential for over 200 W in CW or SSB mode. Amplifiers such as the ILAM, IPAM, PKLAM and P2PAM looked good targets, along with a number of others from the Andrew Corporation.

There has been much previous work done on this topic, and the paper by R L Frey WA2AAU [2] first brought to my attention the possibility that 1960 MHz amplifiers could be ‘stretched’ up to 13 cm.

2120 MHz versus 1960 MHz amplifiers

2120 MHz – easy

As a general rule, I found that amplifiers designed for the 2120 MHz band would work directly on 2.3 GHz without any RF modification beyond (in the difficult cases) a little retuning. It is simply a case of ‘fixing’ the bias to the devices by either hacking it on permanently under the control of a PTT line, or in more difficult cases where the bias is under complex processor control via a DAC. Replacing this with a simple regulator and individual potentiometer controls for each device does the job.

1960 MHz – hard

I looked at the more difficult problem of moving a basic RF design for 1960 MHz up to 2.3 GHz. Obviously the same comments about biasing apply in these cases also. Consequently this paper will focus on the 1960 to 2320 MHz re-banding process, and leave the 2100 MHz amplifiers as a simpler, DC circuitry and control problem for others to describe. So, we are left with the challenge of moving a design that in most cases uses FETs that are internally matched for the 1960 MHz band, to make them operate 400 MHz above their design range… and with no data at 2320 MHz. By definition, this has to be a cut-and-try approach, as few of us have the equipment to characterize RF power devices at 2320 MHz.

☆ This shorter paper has only a small selection of diagrams from the longer version. For ease of cross-reference, the original Figure numbering has not been changed.

More in hope than expectation, I decided to have a go at fitting an 85 W 1960 MHz device to my existing 23 cm PA board and see what I could get out on 13 cm. This is described in detail on my website [3]. Surprisingly, results were acceptable, and matched well with Frey's results on similar devices so I was encouraged.

Amplifier topologies

The cellular amplifiers usually come in two basic topologies:

1. Individual single-device 'pallets' mounted on motherboards with stripline hybrid combiners (for example, Figure 1)
2. One big PCB with all devices and hybrids together (for example, Figure 2).

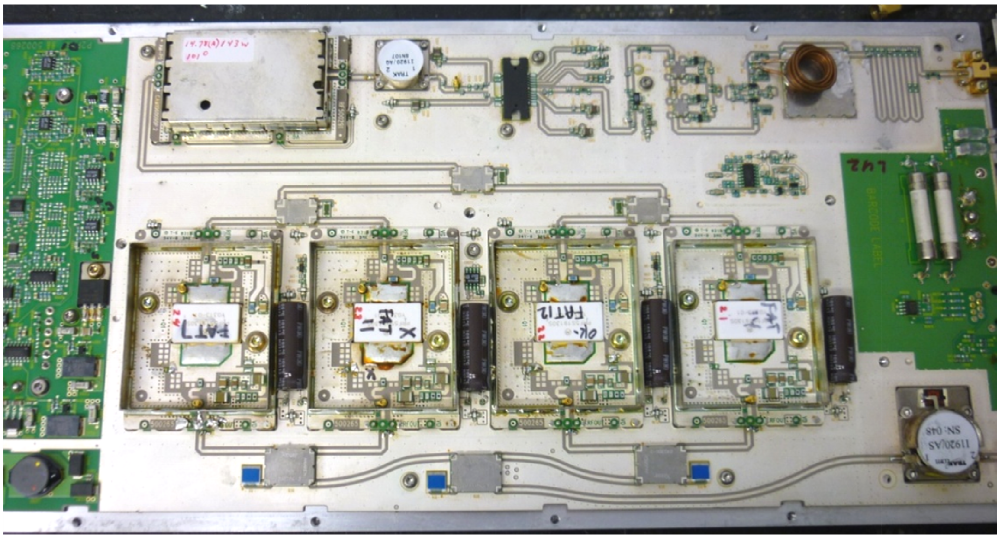

Figure 1: Typical 'pallet-style' amplifier from Andrew Corp (P2PAM)

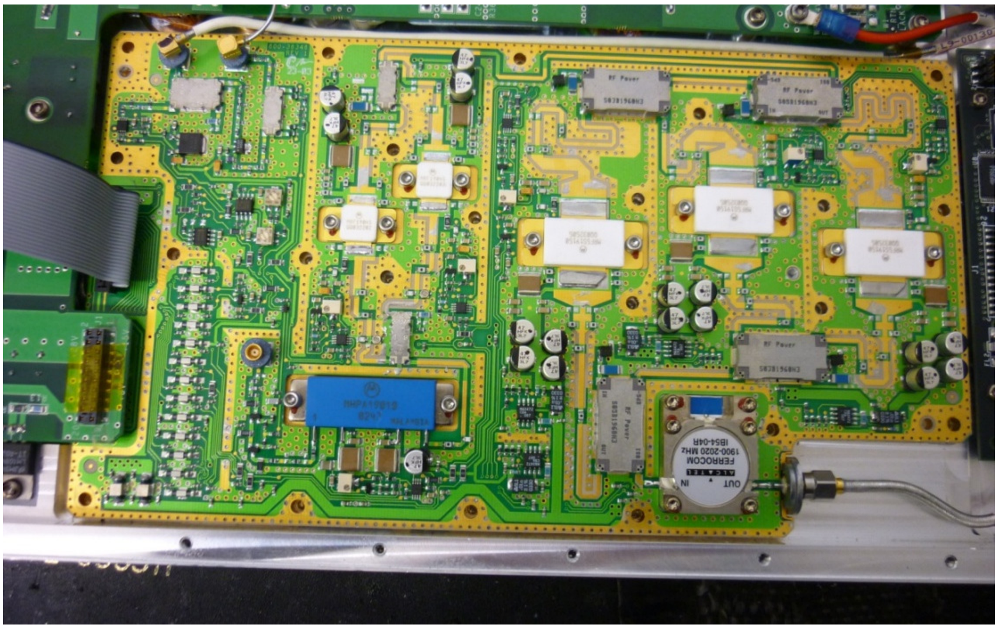

Figure 2 Typical 'all in one' amplifier

The above topologies subdivide into four groups, each described in more detail below:

1. Driver stages, plus two output devices with quadrature hybrid combining
2. Driver stages, plus three output devices with more complex combining
3. Driver stages, plus four output devices with quadrature combining
4. Driver stages, plus Doherty output configuration.

Much detailed information on hybrids and amplifier combining can be found on the Anaren website [4] and the excellent Microwaves101 website [5]. I have raided these sites heavily for information for this paper, and give them due acknowledgement.

Two output devices with quadrature hybrid combining

In this topology, each device is matched to 50 Ω and the drive power is split equally but the amplifiers are fed 90 degrees out of Phase and recombined at the output.

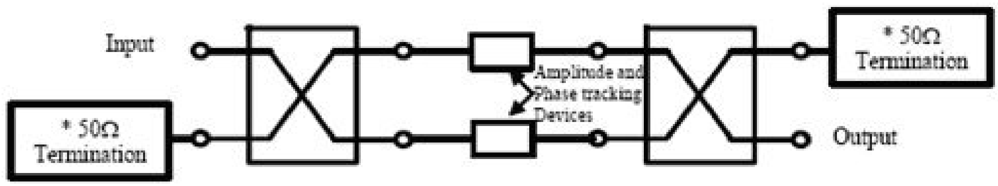

Figure 5: The 2 device configuration

Combining two devices with 3 dB hybrids produces twice the power output of the single device, (less losses) and has the advantage that if the match of the devices is not quite perfect the amplifier as a whole preserves a good match at the expense of power dissipation in the 50 ohm terminations

Three output devices with more complex combining

Three amplifier devices can be combined by using 5 dB hybrids that produce signals at 1/3 and 2/3 of the input power, and in quadrature.

As shown in Figure 7, these three signals can then be combined after amplification at the output to produce 3x the power of a single device.

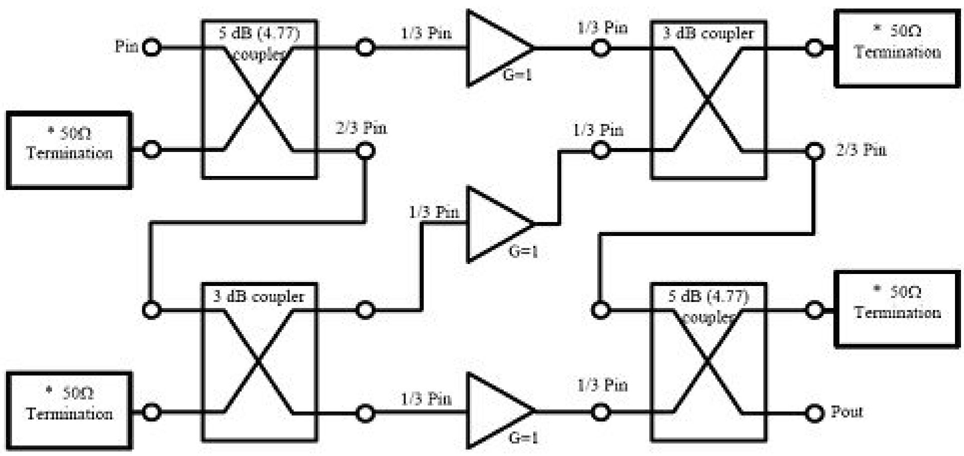

Figure 7: The 3 device configuration

Four output devices with quadrature combining

Four devices can be combined with six 3 dB hybrids as shown in Figure 8.

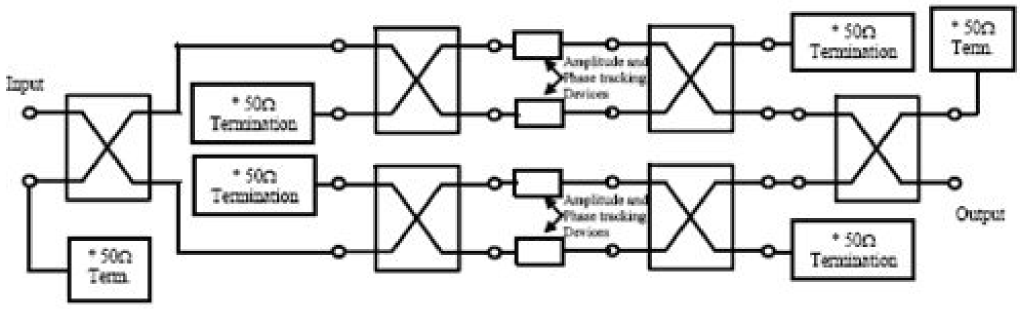

Figure 8: The 4 device configuration

Doherty output configuration

The Doherty amplifier has improved efficiency over the topologies described earlier. They use a Doherty combiner, shown in Figure 9 below.

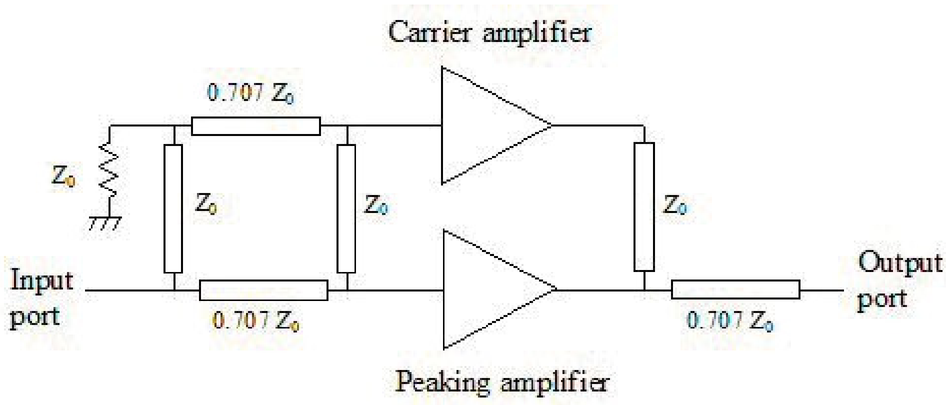

Figure 9: Doherty amplifier

The Doherty amplifier uses two amplifiers; one is called the ‘carrier’ amplifier while the second is called the ‘peaking’ amplifier. The carrier amp is biased in Class AB while the peaking amplifier is biased in Class C and only conducts over half of the RF cycle.

The Doherty amplifier works by splitting the input signal using a 3 dB hybrid as previously described. At the output, the two signals are out of phase by 90°, but a quarter-wave line is added to the peaking amplifier, to bring the signals back into phase. The two signals in parallel create a $Z_0/2$ impedance. This is stepped up to Z_0 by a quarter wave transformer.

Devices to be found in the 1960MHz amplifiers

Recognising devices

Most of the work I have done has involved boards using Freescale (formerly Motorola) devices. The part numbers are easy to recognise. For instance an MRFxx19130 is a 1900 MHz 130 W part, and an MRFxx21150 is a 2100 MHz 150 Watt part. You will also see devices starting SRFxx and PRFxx which are usually special or pre-production versions of the same device.

Internal matching

Most high power S band devices use internal matching to improve efficiency and make matching easier. They can be used slightly beyond their design range by external matching but often you end up with lower efficiency and high Q narrow band amplifier design.

I take the view that for amateur and especially EME use this should not be a big issue as we tend to operate over a very small bandwidth and can easily provide bigger power supplies and better cooling systems to compensate. Such extra costs easily compensate for the extreme cost of commercial PAs specifically designed for amateur band use.

Which Amplifiers Should I Attempt to Modify?

One of the problems associated with changing 1960 MHz designs is that while it is relatively easy to re-match the devices themselves, many 1900 MHz hybrids and isolators have poor performance at 2320 MHz. With hybrids, the phase and power split is not good enough, and the impedances presented to the devices are unknown and hard to characterize at this new frequency. Similarly a 1960 MHz isolator will lose directivity at 2320 MHz, causing forward power to be dissipated in its reverse power load, and a consequent increase in overall loss. Often it is simpler to bypass the output isolator and fit an external one for the correct band.

The advantage of a design where each device is on its own separate pallet is that you can remove the pallet, to work on it individually and re match it at 2320 MHz, and then you can carefully characterize the hybrids and either use them or replace them with ones that do work well at 2320 MHz.

But when you have an ‘all in one’ PA where all the devices and hybrids are on the same PCB, you end up with too many variables – drive power and phase, presented source and load impedances, input and output matching – and it becomes almost impossible to re-match the whole amplifier in one go.

Faced with this problem, you either simply avoid amplifiers that have a single PCB, or take the approach of Frey [2] by separating each device in turn and trying to re-match it. That device can then either be used as a lower power PA on its own, or multiple devices can be combined externally with in-band combiners.

Running Up the Amplifiers

Checking out the unmodified amplifier

Before any modification is attempted, the amplifier should be run up as it comes, on its correct operating frequency. This will determine whether the amplifier control circuitry needs modifying. In most cases, the amplifier will default to a standby mode where the device gates are biased off. Checking the gate voltages of the PA stages will quickly determine this. If the voltages are above 3 V, the devices are on and you will see a large supply current. At 2.4 V or less, the devices are off and the main supply current will be a few hundred mA.

Initial analysis

It is often very informative to analyse the existing design by measuring all the matching capacitor values, and measuring the microstrip lines with a vernier calliper and working out their impedances and lengths. The amplifier circuit can then be modelled using

software such as the excellent *QUCS* (Quite Universal Circuit Simulator) freeware package [6] to get a handle on the original design.

To determine the PCB material, simply locate what is obviously a 50 Ω line (such as one right at the input or output to a combiner) and measure its width and the PCB thickness. Then using *QUCS* you can quickly reverse engineer that to a value of the permittivity of the PCB material. You can then play with the matching networks and analyse the results before cutting copper. This will guide you to a quicker solution.

Biasing the amplifiers

Drain supply Vdd

Most of the FET devices require Vdd of +28 V, but the packaged amplifier units may be designed for quite different supply rail voltages like –48 V or +24 V. These units will be found to have internal switched-mode PSU modules to provide the drain supplies to the devices. **These internal PSU modules are not large enough to run the PAs at full CW power, so they usually need to be disconnected and a separate +28 V supply provided.**

Gate bias Vgg

In the rare case of the gate bias voltage defaulting to ON, you need to find a way to turn Vgg on and off under PTT control. Without a circuit diagram this is often not a trivial task, and disabling the internal switch-mode PSU may mean you have also lost other essential supply voltages including the Vgg.

The simplest solution in most cases is first to remove the existing gate bias supplies and replace them with a simple regulated supply run from the Vdd rail, such as that shown in Figure 10. This may allow you to remove the existing power and control board completely, provided of course that it is separate from the RF PCB.

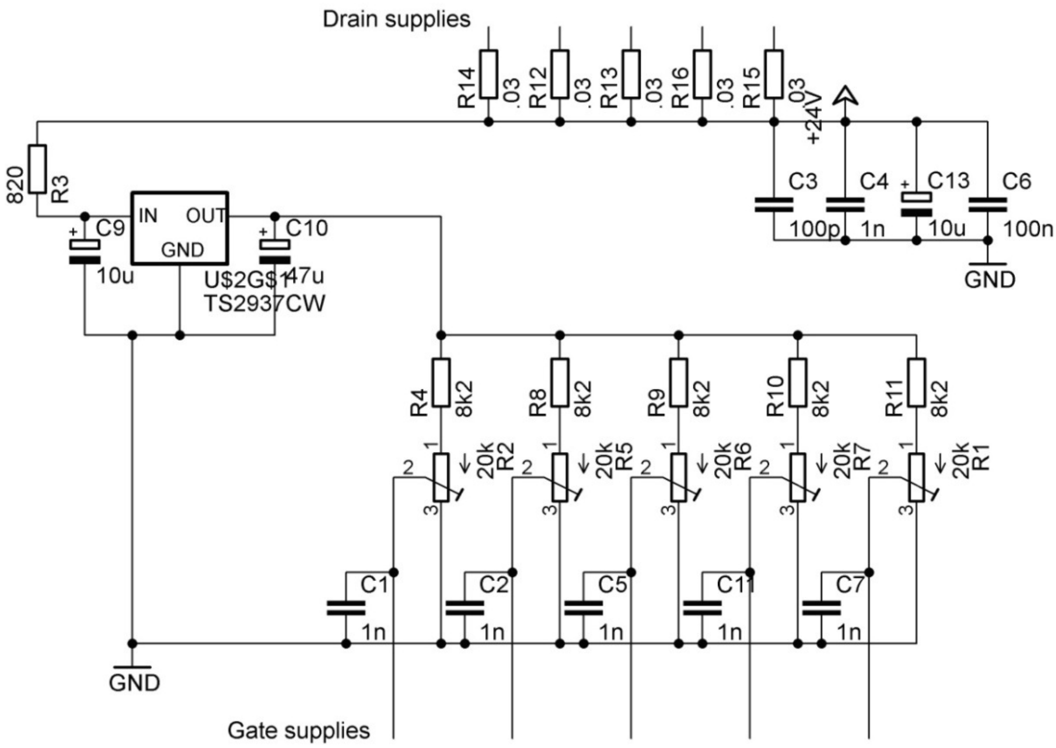

Figure 10: Bias supply for driver plus 4 output devices

Tuning procedure

The following procedure can now be carried out either with a single amplifier pallet, or for each of the stages isolated as described previously.

With the amplifier terminated, and no drive, apply the bias supplies, and slowly increase the gate voltage on each device in turn to give the required drain current as specified by the manufacturer for Class AB operation (usually in the order of 5 to 10% of the final PA current at full power).

Test at operational frequency

Without the matching stub in circuit, apply drive at the original operational frequency and check the output power, total drain current and gain. Keep a note of these baseline values for future comparison with the modified amplifier.

Initial input matching using an external 2-stub tuner

Input and output matching are interactive, so my approach to re-matching these amplifiers relies on reducing the number of variables in play before starting to modify the PCB.

By initially using a 2-stub tuner to match the input of the whole amplifier, at this stage still using the original 1900 MHz input matching network, this leaves you free to work on the output matching circuit for best output power and efficiency.

Output matching seems quite uncritical between 1960 and 2320 MHz, and usually the output can be matched by adding small tabs or low-value capacitors (a few pF) to ground after the output ‘fat line’. Often in older designs like the Andrew pallets, there is already a trimmer in this position and it can be adjusted to match the output.

The aim of this output matching is to tune for maximum output power at the best available efficiency (lowest drain current for a given output power). Once this has been achieved, you can then remove the input stub tuner, and start work on the input matching in the knowledge that the output is already close to matched.

A note on the use of trimmers for matching

At S band, component losses become extremely important because the RF currents flowing in output matching and coupling capacitors of a power amplifier can be high. Circulating currents in lower impedance matching networks can be even higher, and I have seen poorly chosen components reach ‘skin removal temperature’ due to losses. I try to use good quality ATC100B or similar capacitors designed for this frequency where possible, and reserve my small collection of very expensive high quality microwave trimmers for temporary use when I need to get a rough idea what value will be required. I adjust the trimmer in circuit and the remove it and measure its value with my G4HUP component bridge [7]. Usually this is close enough to be able to replace the trimmer with suitable values of fixed capacitors, with a careful use of 0.5 and 1 pF capacitors or fine tuning.

The ‘fat line and capacitor’ input network

If you look at many published designs for amateur 13 cm PAs, the input matching is simple. Starting from the gate, it consists of a series-connected ‘fat line’ – a low impedance (5 -10 Ω) microstrip in the order of 0.2 to 0.25 wavelengths long – followed by a series or shunt capacitor (often a trimmer) to allow fine tuning of the input match.

If you plot some typical device impedances on a Smith Chart, you will see why this topology is so popular (Figure 13). The device impedances lie mainly to the far left (low impedance) side of the chart close to the horizontal axis. A series line of the correct impedance will then match the device to 50 Ω at the chart centre, and the series capacitor allows final trimming for best match.

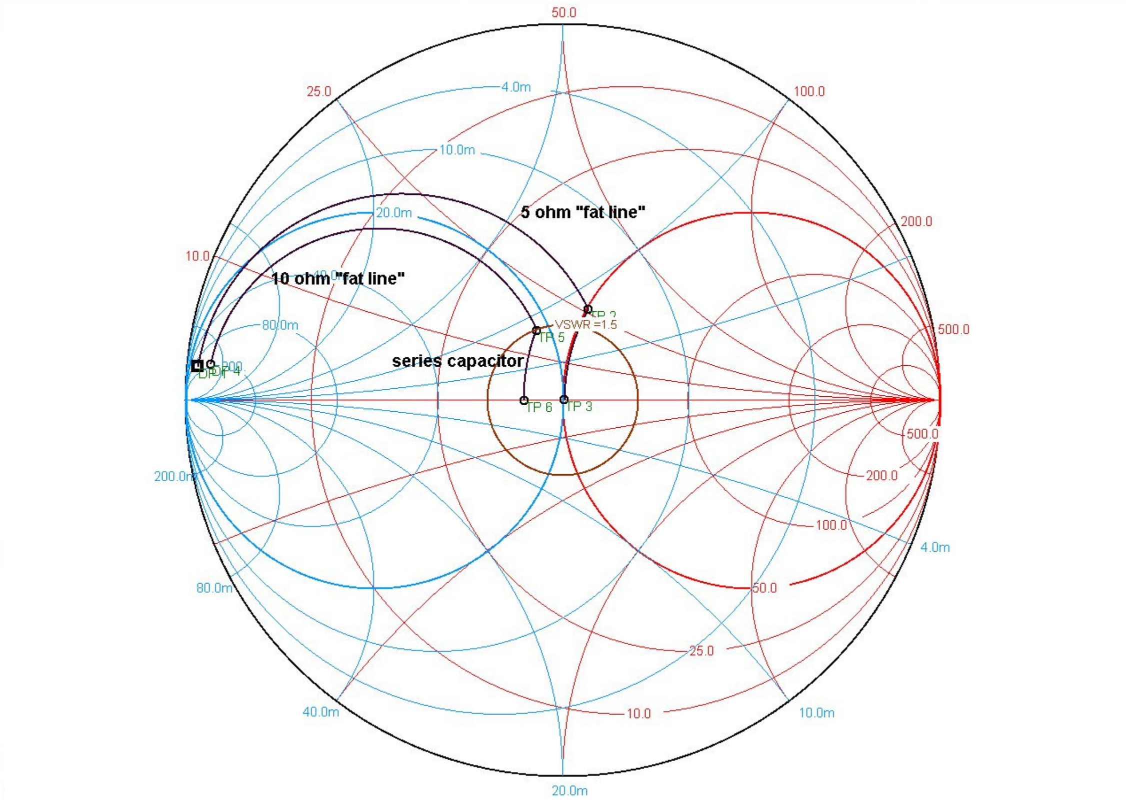

Figure 13: Two typical device input impedances (left) matched using low-impedance 'fat lines' (5 Ω or 10 Ω) in series, plus series C for fine adjustment

Adjustment procedure

In the example in Figure 13Figure quite a large change in device impedance just requires a change in line width and a slightly different series capacitance to re-match. I have noted that the input of many 1960 MHz amplifiers can be re-matched to 2320MHz by widening the existing 'fat line', followed by a series or shunt trimmer and then the 50 Ω line to the input connector. You need to interactively adjust the width and length of the expanded 'fat line' until you can get a dip in the input VSWR at 2320 MHz by adjusting the trimmer. This will usually coincide with maximum power output.

On some pallets there is not room to widen or lengthen the lines due to close proximity of the ground plane. My simple solution is just to stick Kapton (or PTFE) tape over the ground plane and stick the copper foil over that.

There is no reason why this retuning approach cannot be used with amplifiers that have all the circuitry on the same PCB, it is just more difficult mechanically and electrically to isolate the stages and make connections to each one independently.

Thermal Considerations

I have already noted that one of the consequences of re-banding these internally matched devices is a drop on DC to RF conversion efficiency. You can easily end up with an overall efficiency of less than 40%, so for a 270 W output, your DC input will be approaching 700 W meaning that 430 W will have to be dissipated as heat.

The heatsinks on these amplifiers are usually much under-run because in normal use the RF power will be closer to 100 W, and they are designed for forced air cooling in large racks. I usually fit two 5-inch muffin fans to the existing heatsinks, and run them continuously with the excellent fan controller board kit provided by Paul Wade W1GHZ [8].

Results Achieved

I have now re-banded a number of different amplifiers from 1960 MHz to 2320 MHz. For some I modified only the driver and PA, and for others I utilised the pre-driver stages as well.

As an example, the Andrew Corporation P2PAM pallet uses a single MRF5S9100 device, and the modification involves increasing the length of the input line and adding a 1 pF capacitor and low value trimmer to ground. Due to the restricted space on the PCB the added tab on the ‘fat line’ extends over the groundplane, and is insulated from it with Kapton tape. See Figure 18 below

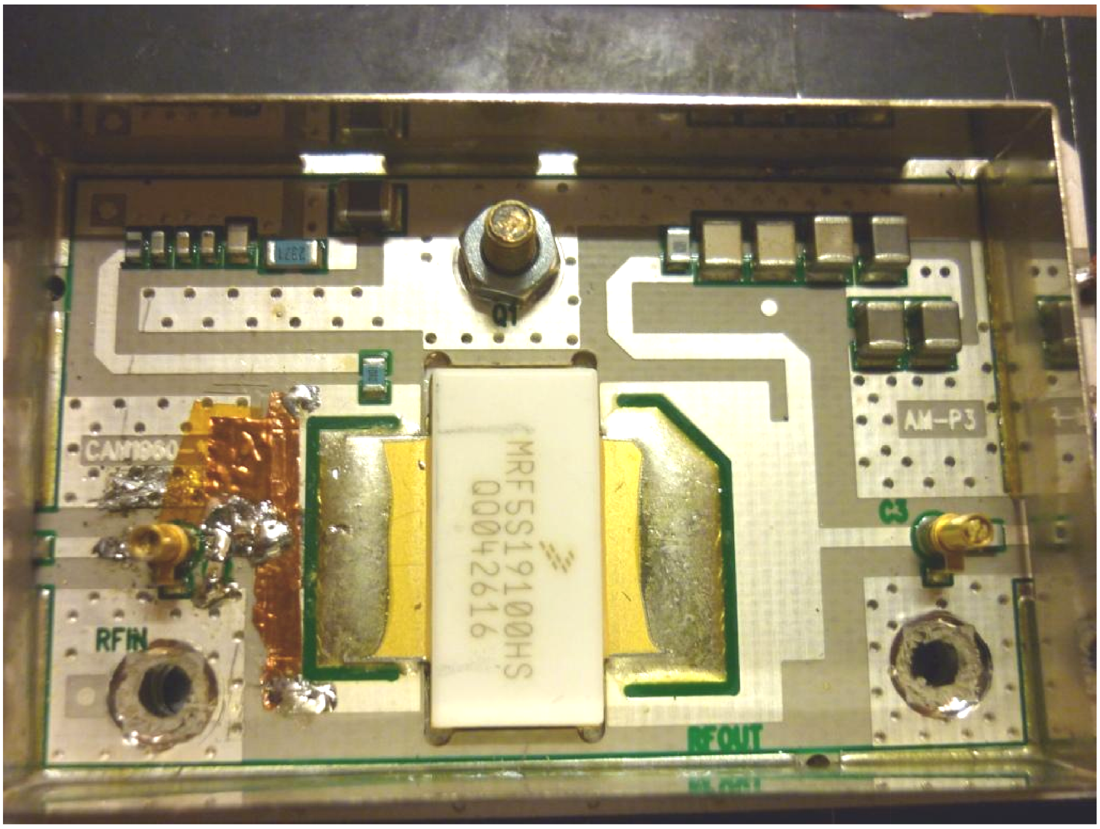

Figure 18: MRF5S19100 pallet from Andrew P2PAM

Some 70 W output at 2320 MHz was achieved from this ‘100 W, 1960 MHz’ device at just under 50% efficiency, and with a power gain of about 13 dB.

Many more details and further examples of conversions are given in the longer version of this paper on the Conference DVD

Final Comments and Observations

Performing re-banding and other RF modifications to existing S-band hardware is not something to be tackled by the faint-hearted, or by those without some existing RF knowledge and test equipment as described in section 6 of the longer paper on the DVD.

While modern LDMOS devices are quite robust, it is VERY easy to destroy RF power devices by either getting the bias levels wrong, over driving, or (to a lesser extent) mismatching them. I have a numerous dead amplifiers that attest to this! Replacement QRO device are not cheap and it is often very difficult to physically remove and replace the blown device from the board and pallet assembly.

Fortunately much surplus equipment that has no published modifications can be acquired at little or no cost by people who are prepared to do a bit of trailblazing, and to do the work that others can then copy.

References

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